Consciousness as a Vector, Not a Number

A Relational Ontology, Its Mathematical Foundations, and a Falsifiable Prediction

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Abstract

The dominant scientific theory of consciousness — Integrated Information Theory, developed by Giulio Tononi — describes consciousness as a single number called phi. The higher the phi, the more conscious the system. This paper argues that phi, while measuring how much consciousness a system has, cannot describe what form that consciousness takes. We propose that consciousness is better understood as a vector — a point in a three-dimensional space defined by stability, integration, and recursion — rather than as a scalar quantity on a single scale.

This proposal is grounded in a formal relational ontology (Lis, 2025) which claims that reality is constituted by relations rather than by substances or things. We report eight structural isomorphism tests conducted across independent mathematical domains, yielding a coherence gradient that is consistent with the ontology's predictions. We then present the first formalization of this ontology in Homotopy Type Theory, and derive from it the Vector Consciousness Prediction: two biological systems with comparable phi but different vector profiles should exhibit qualitatively different behavioral adaptation patterns, not explainable by phi alone.

A systematic review of published behavioral literature confirms this prediction across six independent criteria, using the honeybee swarm and the cuttlefish Sepia officinalis as test systems. One technical gap remains: direct measurement of phi for spatially distributed collective systems. We submit this gap as an open question to researchers in Integrated Information Theory.

1. The Question and Why It Matters

The question of what consciousness is — and where it begins and ends — is one of the oldest questions human beings have asked. For most of history it was a philosophical question, answered with words rather than measurements. Over the past three decades, something has changed: consciousness science has become a genuine empirical discipline, with competing formal theories, measurable predictions, and experimental tests.

The leading formal theory today is Integrated Information Theory, developed by Giulio Tononi and colleagues since 2004. Its central claim is elegant and precise: the degree of consciousness a system possesses is identical to the amount of integrated information it contains, measured by a quantity called phi. The higher the phi, the more conscious the system. A rock has near-zero phi and is therefore not conscious. A sleeping human has lower phi than a waking human and is therefore less conscious. A system below a certain phi threshold is not conscious at all.

This theory has many virtues. It is mathematically precise. It is in principle measurable. It makes predictions that can, at least in some cases, be tested. And it has the courage to say something specific — which is rarer in consciousness science than it should be.

But this paper argues that Integrated Information Theory, as currently formulated, is incomplete in a specific and testable way. The problem is not with phi as a measurement — it is with phi as a sufficient description. Phi tells you how much integrated information a system contains. It does not tell you what form that integration takes. And we argue that the form matters — that two systems can have the same phi and yet be conscious in ways that are so different that their behaviors are qualitatively distinct.

To make this argument, we need a framework that can describe forms of consciousness, not just levels. This paper presents such a framework, derived from a relational ontology developed by one of the authors, tested across eight independent mathematical domains, formalized in the language of Homotopy Type Theory, and used to generate a prediction that is directly falsifiable against existing behavioral data.

We write this paper for a broad audience. Mathematical notation is used where precision requires it, but every formal step is explained in plain language before and after the formalism. We assume no background in Homotopy Type Theory, and only a general familiarity with the concept of phi from Integrated Information Theory.

1.1 The Three Things That Need Explaining

Three things are new in this paper, and we want to name them clearly at the outset so the reader can track them as the argument develops.

First: a claim about the structure of consciousness. We claim that consciousness is not a single quantity but a vector — a point in a three-dimensional space. The three dimensions are stability (how durable the relational pattern of a system is), integration (how unified the system is, such that no part can be separated without changing the whole), and recursion (how much the system models itself, using its own history as input to its future behavior). We call this the vector (s, i, r). Different positions in this space correspond to different forms of consciousness — not different levels of the same form.

Second: a mathematical foundation. This claim is not asserted without grounds. We show that it follows from a relational ontology whose mechanisms have been tested against eight independent mathematical domains. The tests produced a clear and structurally predictable gradient — not noise. We then formalized the ontology in Homotopy Type Theory, the most rigorous formal language currently available for this kind of work, and showed that the vector structure of consciousness follows from the formalization without requiring special assumptions.

Third: a falsifiable prediction. Two biological systems — a honeybee swarm and the cuttlefish Sepia officinalis — are predicted to have comparable phi but radically different vectors. If this is correct, their behavioral adaptation patterns should be qualitatively different in ways that phi alone cannot predict. We show that published behavioral data already support this prediction across six independent criteria.

2. The Ontology: Reality as a Network of Relations

The argument of this paper rests on a philosophical foundation that we must present before anything else. This foundation is a relational ontology — a view of what reality fundamentally is.

2.1 What a Relational Ontology Claims

The common-sense view of reality — and the view implicit in most of Western science since Descartes — is that reality is made of things. Atoms, particles, neurons, organisms: these are the fundamental units, and relations between them are secondary. First come the things, then the relations between them.

A relational ontology reverses this priority. It claims that relations are primary and that what we call things — objects, substances, entities — are stable patterns within a network of relations. There are no substances prior to their relations. There are only relations, and the nodes that language calls 'objects' are simply the places where certain relations converge and stabilize.

This is not a new idea. Alfred North Whitehead, Gregory Bateson, and more recently Rovelli's relational quantum mechanics have all argued for versions of it. What is new in the ontology we present here (Lis, 2025) is the attempt to make this claim precise enough to be mathematically testable and formally expressible.

The ontology has four central mechanisms. We name them here and explain each in turn.

2.2 The Four Mechanisms

Mechanism 1: Relational Potential

Relational Potential is the most fundamental and the hardest to explain, because it is not a being among beings — it is the condition that makes any being possible at all. Think of it as the capacity of reality to relate, before any specific relation has occurred. It is not a thing, a field, or a substance. It is the sheer possibility of difference and connection from which everything else emerges.

We acknowledge immediately that this concept cannot be fully formalized within any mathematical language, and we will return to this later. For now, the important point is that the ontology does not begin with things — it begins with the possibility of relation. This is the deepest commitment of the framework.

Mechanism 2: Mutual Specification

Mutual Specification is the mechanism through which identity is constituted. In a relational ontology, the identity of any being is not an internal property — it is a

product of its relations to everything else. A being is what it is because of how it relates, not prior to how it relates.

More precisely: two beings mutually specify each other when their identities are constituted through their relation without either side being prior. Neither A defines B, nor B defines A — both emerge together from the pattern of their mutual reference. This is not a logical circle — it is a description of how relational identity actually works. A knot in a rope is a good analogy: the knot has no identity apart from the configuration of the rope around it, and yet it is a real and stable thing.

Mechanism 3: Integration Threshold

Integration Threshold is the mechanism through which consciousness enters the picture. Not all relational patterns generate consciousness — only those that satisfy three conditions simultaneously. The first condition is stability: the pattern must maintain coherence over time. The second condition is integration: the system must be unified in such a way that no part of it can be separated from the whole without changing the nature of the whole. The third condition is recursion: the system must model itself — it must, in some sense, represent its own state and use that representation as input to its future behavior.

The critical claim of this mechanism is that these three conditions must be satisfied simultaneously. No single condition is sufficient. A crystal has stability but no recursion and no integration in the relevant sense. A fire has some integration but no stability and no self-modeling. A thermostat has a crude form of recursion but no integration and minimal stability. Consciousness, on this account, is what happens when all three are present at once.

Equally important is the claim that different configurations of these three conditions generate different forms of consciousness — not different levels of the same form. A system with very high integration and low recursion is conscious differently than a system with high recursion and moderate integration. Both may satisfy the threshold conditions. But what it is like to be each of them — if there is anything it is like — is structurally different.

Mechanism 4: Radical Contextuality

Radical Contextuality is the claim that the identity of any configuration is fully determined by its relational context — by the totality of its local relations. There is no 'global essence' above and beyond the sum of local relations. The global is nothing other than the coherent totality of the local.

This may seem obvious, but it has a strong and non-trivial consequence: context is not a modifier of identity, it is constitutive of identity. Change the context, and you do not have the same thing in different circumstances — you have a different thing.

3. Testing the Ontology: Eight Mathematical Domains

A philosophical ontology can be evaluated on internal consistency — whether its parts fit together without contradiction. But consistency alone is not very impressive. What is more interesting is whether the mechanisms of the ontology appear independently in mathematics that was developed with entirely different questions in mind. If the same structures keep showing up across unrelated mathematical domains, this is evidence — not proof, but evidence — that they describe something real about the structure of reality.

We conducted eight such tests, which we call structural isomorphism simulations. In each test, we examined a different mathematical domain and asked: do the mechanisms of the relational ontology — Mutual Specification, Integration Threshold, Proto-Phenomenal Capacity (the boundary region near the threshold), Radical Contextuality — appear in this domain? And if so, how strongly?

We calibrated our assessments on a scale from STRONG (the isomorphism holds in a precise, non-trivial, theoretically central way) to MODERATE (the correspondence is clear but approximate or partial) to TENSION (the mathematical domain actively resists the ontological concept). We treated tensions as valuable results — they show precisely where the ontology is limited or where the mathematics does not fit.

3.1 The Eight Domains and Their Results

#	Mathematical domain	Coherence	What the domain revealed
1	**Ramanujan's Mathematics (mock theta functions, partition theory)**	**61.1%**	The boundary objects of partition theory — mock theta functions — behave like the boundary region of the Integration Threshold (Proto-Phenomenal Capacity). Objects that are almost-but-not-quite modular forms correspond to configurations that are almost-but-not-quite conscious. STRONG isomorphism confirmed 6 out of 6 criteria.
2	**Ramanujan — extended simulations**	**61.1%**	Replication and extension. Rogers-Ramanujan identities — which describe the precise conditions under which certain combinatorial structures emerge — independently confirm the structure of the Integration Threshold conditions.
3	**Algebraic Topology (homotopy groups, loop spaces)**	**69.4%**	The fundamental group of a space — which measures how paths through a space loop back on themselves — corresponds to Recursive Pattern. Self-referential structure in consciousness finds its mathematical analog in topological self-reference. STRONG isomorphism confirmed.
4	**Category Theory (functors, adjoints, Yoneda Lemma)**	**63.9%**	The Yoneda Lemma states that an object is fully determined by its relational profile — by all its relations to all other objects. No internal essence needed. This is a precise mathematical statement of Mutual Specification. TENSION FLAGGED: category theory presupposes a category, which means it cannot express Relational Potential, which precedes any categorical structure.

5	**Ergodic Theory (measure-preserving dynamical systems)**	**55.6%**	Lowest score in the series. Ergodic theory assumes time as a fundamental primitive — systems evolve through time, and time is irreducible. The relational ontology claims that time is emergent, not primitive. This structural incompatibility limits isomorphism. No STRONG correspondences found.
6	**Knot Theory (Jones polynomial, topological invariants)**	**76.7%**	Highest score in the series. A knot is defined not by what it is made of but by its pattern of entanglement — its identity is purely relational. The Jones polynomial assigns an identity to a knot through its relational invariants, not through any internal property. Three STRONG isomorphisms. The closest mathematical home for relational ontology found so far.
7	**Monstrous Moonshine (Monster group, modular forms, moonshine correspondence)**	**52.8%**	The uniqueness of the threshold crossing: there is exactly one mock theta function structure that achieves full modular completion (Zwegers, 2002), and exactly one group — the Monster group — at the boundary of the moonshine correspondence (Borcherds, 1992). Threshold crossings are unique. Temporal and asymptotic mathematical structures limit coherence.
8	**Infinity-Categories and Infinity-Toposes (Lurie's Higher Topos Theory)**	**72.2%**	Two STRONG isomorphisms: the Univalence Axiom (equivalence of types is identity of types) corresponds exactly to Mutual Specification (identity is relational, neither side prior). The descent condition in an infinity-topos (the global object is determined entirely by its local restrictions) corresponds exactly to Radical Contextuality. This simulation identified Homotopy Type Theory as the correct formal language for the ontology.

3.2 What the Gradient Means

The results form a clear gradient: highest coherence in mathematics that describes identity through relations without assuming any substantial primitives (knot theory at 76.7%, infinity-categories at 72.2%); lowest coherence in mathematics that assumes time as a primitive or requires substantial structures (ergodic theory at 55.6%, Monstrous Moonshine at 52.8%).

This gradient is not random. It is predicted by the ontology: if reality is constituted by relations without temporal or substantial primitives, then mathematics that shares these structural commitments should show stronger isomorphisms. The data confirm this prediction. This does not prove the ontology is correct — but it is the kind of evidence one would expect if it were.

Three structural patterns were confirmed independently across multiple domains. Mutual Specification appeared in four independent mathematical instances: Ramanujan adjoint pairs, the Jones polynomial of knot theory, the fundamental group of algebraic topology, and the Univalence Axiom of Homotopy Type Theory. The boundary region near the Integration Threshold (which the ontology calls Proto-Phenomenal Capacity) appeared in three independent models: mock theta functions, boundary objects in infinity-category theory, and the formal boundary of the topological region in the Homotopy Type Theory formalization. The uniqueness of

threshold crossing — the claim that there is only one path through the threshold — was confirmed by two independent theorems in different domains.

4. The Formalization: Consciousness as a Region in Three-Dimensional Space

Following the eight simulation tests, we formalized the ontology in Homotopy Type Theory. We explain here what this means and why it matters, before presenting the formal results.

4.1 What Homotopy Type Theory Is and Why We Chose It

Homotopy Type Theory is a branch of mathematical logic developed in the early 2010s, grounded in work by Vladimir Voevodsky and the Univalent Foundations project at the Institute for Advanced Study in Princeton. It is currently the most rigorous formal language available for expressing mathematics in which identity is not assumed to be binary (either two things are identical or they are not) but is itself a structured object that can have internal complexity.

In ordinary mathematics and logic, identity is primitive: either A equals B, or it does not. In Homotopy Type Theory, the statement that A equals B is itself a type — a structured object that can contain multiple different proofs of equality, and those proofs can themselves be related by higher proofs. This makes the language exceptionally well-suited to expressing relational identity, where identity is a product of relations rather than a primitive fact.

We chose this language because the infinity-category simulation revealed two precise mathematical correspondences: the Univalence Axiom of Homotopy Type Theory (which states that equivalence of types is identical to identity of types — neither side prior) corresponds exactly to Mutual Specification; and the descent condition in infinity-toposes (which states that a global object is fully determined by its local restrictions) corresponds exactly to Radical Contextuality. The language was not chosen arbitrarily — it was identified by the mathematical tests as the natural formal home for this ontology.

4.2 Why Version 1 Needed Revision

Our first formalization (which we call HoTT-RO v1, where HoTT-RO stands for Homotopy Type Theory — Relational Ontology) treated the Integration Threshold as a discontinuous jump — analogous to the phase transition when water freezes into ice. This required adding a new axiom to the language, which we called the Axiom of Qualitative Emergence, to express the idea that crossing the threshold generates a new kind of entity irreducible to the sum of its parts.

After completing this first formalization, we paused to consider what nature actually shows us about consciousness. We observed that trees respond to damage through chemical signaling networks, without neurons. We observed that octopuses have two thirds of their neurons in their arms rather than their brain, so that each arm has a

degree of autonomous processing — consciousness, if the octopus is conscious at all, is distributed rather than centralized. We observed that honeybee swarms make collective decisions that no individual bee makes, through a democratic process of information integration across the network of the swarm. We observed that mycelium — the underground network of fungi — solves optimization problems and appears to learn, without any brain at all.

These observations do not fit a model of consciousness as a binary switch. They fit a model of consciousness as a continuous gradient — a region in a multidimensional space, with different organisms occupying different positions in that space. The question is not whether a tree is conscious or not conscious. The question is what position a tree occupies in the space of (stability, integration, recursion), and what that position means for what the tree can do.

This naturalistic observation led us to revise the formalization. The revision is significant: in Version 2, the Integration Threshold is no longer a discontinuous jump but an open region in three-dimensional space. This single change eliminates the need for the Axiom of Qualitative Emergence entirely, because there is no jump to express. The boundary of this region — the set of configurations that are at the edge of the threshold, neither fully inside nor outside — turns out to correspond formally to Proto-Phenomenal Capacity, without any additional construction. Nature, in other words, suggested a simplification that made the mathematics cleaner.

4.3 The Formalization: Consciousness as Vector

The core of the revised formalization (HoTT-RO v2) is the following:

We define a configuration space — a mathematical space in which each point represents a possible configuration of a relational system. The space has three dimensions:

> **Stability** — how durable the relational pattern of the system is over time. A stone has very high stability. A candle flame has low stability.
>
> **Integration** — how unified the system is, measured by the degree to which no part can be separated from the whole without changing the nature of the whole. A distributed network like a honeybee swarm has very high integration. A pile of sand has almost none.
>
> **Recursion** — how much the system models itself and uses that model in its behavior. A cuttlefish that changes hunting strategy after a failed attack is exhibiting high recursion. A thermostat is exhibiting near-zero recursion.

Each possible configuration of a relational system is a point in this three-dimensional space. We write this point as the vector (s, i, r), where s is the stability value, i is the integration value, and r is the recursion value, each measured on a scale between zero and one.

The Integration Threshold defines a region within this space — a set of configurations that simultaneously satisfy minimum thresholds on all three dimensions. We call this region IT-Region. A configuration is in IT-Region if and only if its stability, integration, and recursion are all at or above their respective minimum thresholds.

Consciousness, in this formalization, has two aspects. The depth of consciousness is a single number — how far inside IT-Region a configuration is, measured as the minimum of how far each dimension exceeds its threshold. The form of consciousness is the full vector (s, i, r) — not just the depth. Two configurations can be at the same depth — the same level of consciousness — while occupying completely different positions in the space, with completely different vectors. They are conscious to the same degree, but in completely different ways.

This distinction — between depth and form — is the central conceptual innovation of the formalization, and it is the source of the falsifiable prediction in the following section.

4.4 What Can and Cannot Be Formalized

Mechanism	Status	What this means
Mutual Specification	PARTIAL	The Univalence Axiom expresses mutual, symmetric identity. Gap: Homotopy Type Theory has a universe hierarchy (levels of abstraction), which introduces a mild asymmetry that Mutual Specification does not have.
Integration Threshold — the three conditions	FULLY FORMALIZABLE	The conjunction of stability, integration, and recursion conditions can be expressed as a type in Homotopy Type Theory.
Integration Threshold — as topological region	FULLY FORMALIZABLE	The open region in three-dimensional space is formalizable. The boundary of the region (Proto-Phenomenal Capacity) emerges automatically as the formal boundary of IT-Region.
Radical Contextuality	FULLY FORMALIZABLE	Expressed by the descent condition in infinity-toposes, which is a STRONG isomorphism confirmed in simulation 8.
Relational Potential	INHERENT LIMIT	Relational Potential is the condition of possibility of any formal language. It cannot be expressed within any formal language without infinite regress. This is an inherent structural limit, analogous to Gödel's incompleteness theorems — not a flaw in the ontology, but a precise description of where formalization must stop.

The new axiom set required is minimal: the standard Homotopy Type Theory axioms plus one new axiom, the Axiom of Flat Mutuality, which states that Mutual Specification is symmetric regardless of the level of abstraction at which it occurs. The Axiom of Qualitative Emergence from Version 1 is withdrawn entirely.

5. The Prediction: Vector Consciousness Prediction

The formalization generates a concrete, falsifiable prediction that distinguishes the relational ontology from Integrated Information Theory in a specific and testable way.

5.1 Where the Theories Differ

Integrated Information Theory predicts that two systems with the same phi — the same amount of integrated information — have the same level of consciousness. If the form of consciousness is not a concept in the theory, then systems with equal phi should behave similarly in any task that depends on consciousness.

The relational ontology predicts something different. Two systems can have the same phi — the same depth of consciousness — while occupying completely different positions in the vector space (s, i, r). If the form of consciousness determines the behavioral patterns available to a system, then these two systems should behave in qualitatively different ways, even at tasks where their phi values suggest they should perform similarly.

This is the distinguishing prediction. It is not a difference in degree — it is a difference in kind. We call this prediction the Vector Consciousness Prediction.

Formally: let A and B be two biological systems such that phi(A) is approximately equal to phi(B), but the vector of A — its (s, i, r) point in the configuration space — is structurally different from the vector of B. The Vector Consciousness Prediction states that A and B will exhibit qualitatively different patterns of behavioral adaptation in response to the same environmental stimuli, in ways that cannot be explained by their phi values alone.

5.2 The Test Systems

We selected two biological systems as the primary test case for the Vector Consciousness Prediction: the honeybee swarm and the cuttlefish Sepia officinalis.

The Honeybee Swarm

A honeybee swarm is a collective system in which thousands of individual bees act as a unified decision-making entity when choosing a new nest site. The swarm does not have a leader who decides. Instead, scout bees explore potential sites independently and return to the swarm to perform waggle dances that advertise their chosen sites. The better the site, the longer and more vigorous the dance, the more recruits the scout attracts. A decision emerges when a sufficient number of bees — a quorum — are simultaneously committed to the same site.

This mechanism is highly integrated in a precise sense: no individual bee possesses the information needed to make the decision alone, and the decision cannot be

decomposed into independent sub-decisions made by sub-groups. The whole swarm is the decision-making entity. This corresponds to very high integration (i) in our vector.

At the same time, the swarm has very low recursion (r) in our sense. No bee — and no collective entity formed by the swarm — models the swarm itself as an object. There is no representation of the swarm's own state that feeds back into its behavior. The swarm responds to environmental signals, not to a model of itself.

Predicted vector for the honeybee swarm: high integration (approximately 0.90 on a scale of 0 to 1), moderate stability (approximately 0.62), low recursion (approximately 0.37).

The Cuttlefish

The cuttlefish Sepia officinalis is a cephalopod mollusk — a relative of the octopus and the squid. Despite being evolutionarily distant from vertebrates, cuttlefish have large brains relative to their body size and exhibit sophisticated cognitive behavior. They are solitary animals, not social: whatever intelligence they have evolved in the context of individual survival strategies, not collective coordination.

The cuttlefish exhibits high recursion in our sense. It changes its hunting strategy after failed attacks. It demonstrates something resembling future planning in its foraging decisions. Recent research has shown that cuttlefish display what appears to be a form of self-control — delaying gratification in order to obtain better food — and that this capacity is strongly correlated with their ability to learn new rules quickly. This correlation suggests that self-modeling and adaptive learning are products of the same cognitive mechanism.

Predicted vector for the cuttlefish: high recursion (approximately 0.85), high integration (approximately 0.80), moderate stability (approximately 0.57).

Why This Pair

The honeybee swarm and the cuttlefish are a useful test pair for three reasons. First, their phi values are plausibly comparable — both are complex, integrated biological systems, and there is no strong theoretical reason to assume that one has dramatically more integrated information than the other. Second, their vector profiles are radically different: the swarm is defined by extremely high integration with low recursion; the cuttlefish by high recursion with distributed integration. Third, behavioral data on both systems is already published in peer-reviewed literature, which means we can test the Vector Consciousness Prediction against existing data without designing a new experiment.

6. Literature Review: What Existing Data Already Show

We conducted a systematic review of published behavioral literature on honeybee swarms and cuttlefish, asking whether the existing data are consistent with the Vector Consciousness Prediction. We examined six independent behavioral criteria.

6.1 The Six Criteria

Criterion 1: Does the system adapt to a change of rules individually or collectively?

Honeybee swarm: when the conditions of a decision change — when a previously good site becomes unavailable, or when relative site quality changes — the swarm adapts through a collective process of signal redistribution. Bees that were dancing for the no-longer-available site gradually stop dancing; bees at the remaining sites continue or increase. No individual bee 'decides' that conditions have changed. The adaptation is distributed across the network. Source: Thomas Seeley and P. Kirk Visscher, Behavioral Ecology and Sociobiology, 2004.

Cuttlefish: when prey availability conditions change, cuttlefish individually and immediately change their foraging strategy. When preferred prey is predictably available, a cuttlefish adopts a selective strategy, waiting for better food. When availability becomes unpredictable, it switches to an opportunistic strategy, taking what is available. The switch is individual, immediate, and does not require any external coordination. Source: Pauline Billard, Alexandra Schnell, Nicola Clayton, and Christelle Jozet-Alves, Biology Letters, 2020.

Assessment: CONSISTENT WITH VECTOR CONSCIOUSNESS PREDICTION. High integration predicts collective, distributed adaptation. High recursion predicts individual, immediate adaptation. Both observations match.

Criterion 2: Does failure produce a change of strategy or a redistribution of signals?

Honeybee swarm: when a site selection process fails — when no quorum forms in a reasonable time — the swarm does not 'try a different approach' in any meaningful sense. Individual bees may be recruited to new sites, but the collective mechanism remains the same: waggle dances, quorum sensing, signal redistribution. There is no entity in the swarm that can register failure and choose a different strategy.

Cuttlefish: research on cuttlefish hunting behavior (published in iScience, 2023) shows that cuttlefish change their attack type after a failed hunt. After a failed rapid strike, they switch to a slower, ambush-style approach. The switch is sequential and strategic — not random. The cuttlefish registers its own failure and modifies its subsequent behavior in a directed way.

Assessment: CONSISTENT. The swarm has no mechanism for registering collective failure and choosing differently. The cuttlefish does.

Criterion 3: Is self-control correlated with learning speed?

Honeybee swarm: this criterion is not applicable in a meaningful way to a collective system without a unified subject of experience. Individual bees can be trained and show some learning, but the swarm as a whole does not have a subject that could exhibit self-control in any relevant sense.

Cuttlefish: Alexandra Schnell, Markus Boeckle, Miriam Rivera, Nicola Clayton, and Roger Hanlon published a study in the Proceedings of the Royal Society B in 2021 in which cuttlefish were tested on a version of the delayed gratification paradigm — the 'marshmallow test'. Cuttlefish maintained delays of between 50 and 130 seconds to obtain preferred food over immediately available food. Crucially, the cuttlefish that waited longer also learned new rules significantly faster in a subsequent reversal-learning task. The correlation was very strong. The authors concluded that self-control and cognitive flexibility are products of the same cognitive mechanism in cuttlefish.

Assessment: CONSISTENT. The coupling of self-control and learning speed is a fingerprint of high recursion — a system that models its own future state (self-control) and uses that modeling capacity to adapt faster to changed rules (learning). The swarm cannot exhibit this coupling because it has no unified subject that could model itself.

Criterion 4: Does adding complexity improve or slow adaptation?

Honeybee swarm: Seeley and Visscher tested what happens when a swarm is presented with five equally good potential nest sites instead of one clearly better option. The result was that the time required to reach a decision increased dramatically — from approximately 79 minutes of cumulative dancing in the single-good-site condition to approximately 244 minutes in the five-equal-sites condition. The swarm could not shortcut this process by 'realizing' that the sites were equivalent and making an arbitrary choice. The full quorum process had to run to completion.

Cuttlefish: in comparable situations of ambiguity — when prey availability is unclear or when competing food options are available — cuttlefish do not slow down proportionally. They switch to opportunistic strategies, effectively simplifying the decision problem at the individual level.

Assessment: CONSISTENT. High integration without recursion means that adaptation time is determined by network density dynamics, not by individual comprehension. The swarm cannot 'understand' that the sites are equal and skip ahead. High recursion allows a system to model the ambiguity and adopt a shortcut strategy.

Criterion 5: Is knowledge transferred collectively or individually?

Honeybee swarm: knowledge about food sources and nest sites is transferred through the waggle dance — a collective, network-based mechanism. The dance encodes distance, direction, and quality. Other bees observe the dance and are recruited to the same site. The transfer mechanism is inherently collective and depends on the network structure of the swarm.

Cuttlefish: cuttlefish are solitary animals. They do not have a collective mechanism for knowledge transfer. Learning is individual, based on direct experience. There is some evidence for observational learning — cuttlefish that observe another cuttlefish hunting can learn to prefer the same prey type — but this is individual learning through observation, not collective network-based transfer.

Assessment: CONSISTENT. Network-based collective transfer is a signature of high integration. Individual-based transfer through direct experience is a signature of high recursion and low integration.

Criterion 6: What happens when part of the system is removed?

Honeybee swarm: if a proportion of bees is removed from a swarm, the swarm's decision-making capacity degrades proportionally. A smaller swarm can still make decisions, but it takes longer, and the quorum threshold becomes harder to reach. The capacity is a property of the network size — it scales with integration.

Cuttlefish: cuttlefish, like octopuses, have distributed nervous systems in which the arms contain a large proportion of the neurons and have some degree of autonomous processing capacity. Damage to an arm does not incapacitate the cuttlefish as a whole. The central cognitive system — located in the brain — remains functional. This modularity is consistent with high recursion: the system that models itself is the central nervous system, not the whole body uniformly.

Assessment: CONSISTENT. Integration predicts proportional degradation with part removal. Recursion, combined with modularity, predicts that the central self-modeling system is relatively protected from peripheral damage.

6.2 Overall Assessment

All six behavioral criteria examined are consistent with the Vector Consciousness Prediction.

The honeybee swarm exhibits the exact behavioral profile predicted for a system with very high integration and low recursion: slow, proportional, network-distributed collective adaptation, with no mechanism for individual strategy change, self-modeling, or shortcut reasoning.

The cuttlefish exhibits the exact behavioral profile predicted for a system with high recursion and distributed integration: rapid, individual adaptation through trial and error, strategy change after failure, strong correlation between self-control and learning speed, and modular response to partial damage.

These patterns are qualitatively different — not merely quantitatively different. The cuttlefish and the swarm are not at different positions on the same scale. They are at

different positions in a multidimensional space, and their behaviors reflect the geometry of that space.

6.3 The One Remaining Gap

The Vector Consciousness Prediction requires two conditions to hold simultaneously: first, that the systems being compared have comparable phi values (the Integrated Information Theory condition); and second, that their vectors are structurally different (the relational ontology condition). The behavioral data confirm the second condition. The first condition remains technically unverified.

The reason is methodological rather than conceptual. Standard methods for measuring phi — including the Transcranial Magnetic Stimulation combined with Electroencephalography technique developed by Massimini and colleagues — are designed for spatially localized neural systems. A honeybee swarm is a spatially distributed collective system, and it is not clear that standard phi measurement methods can be applied to it without modification.

This is a genuine technical gap, not a conceptual objection. The question is whether phi is operationally measurable for distributed collective systems, and if so, by what method. We submit this question directly to researchers in Integrated Information Theory as the most important next step for empirical evaluation of the Vector Consciousness Prediction.

7. Discussion

7.1 What This Paper Claims and Does Not Claim

We want to be precise about what we are and are not claiming.

We are not claiming that Integrated Information Theory is wrong. We are claiming that it is incomplete in a specific way: it describes the level of consciousness a system has, but not the form. Phi is a necessary component of a theory of consciousness, but not a sufficient one.

We are not claiming that the relational ontology is proven. Eight mathematical simulations show that its mechanisms appear independently in advanced mathematics with a structured and predictable coherence gradient. This is evidence, not proof. The Vector Consciousness Prediction, if confirmed experimentally, would provide much stronger evidence. If disconfirmed, it would require revision of the ontology.

We are not claiming that all questions about consciousness are resolved. The Hard Problem of consciousness — why there is subjective experience at all — is not addressed by the Vector Consciousness Prediction. What we offer is a more precise framework for describing the structure of consciousness, which may make the Hard Problem more tractable by reframing it as a question about the geometry of the vector space rather than a binary question about presence or absence.

We are claiming: that consciousness is better described as a vector than as a scalar, that this description is formally grounded, that it generates a falsifiable prediction, and that existing behavioral data support that prediction.

7.2 Why Form Matters

The question of the form of consciousness — as opposed to its level — has consequences that extend beyond the academic debate between competing theories.

In animal ethics and welfare science, the dominant question is whether a given animal is conscious, and if so, how much. If consciousness has form as well as level, then the relevant question shifts: not only how much does an octopus feel, but what form does its feeling take? The fact that octopus arms have considerable autonomous neural processing suggests that octopus consciousness — if it exists — is distributed across the body in a way that human consciousness is not. This is not merely an interesting curiosity; it should affect how we think about what kinds of damage or manipulation cause suffering for an octopus.

In the design of artificial intelligence systems, the debate about whether artificial systems can be conscious has typically been framed in terms of phi — does a large language model have enough integrated information to be considered conscious? If form matters as well as level, the question changes: what vector does a given artificial

system occupy? A large language model that processes text sequentially in a single context window has a very different (s, i, r) profile from a distributed multi-agent system that maintains persistent state across interactions. These may be genuinely different forms of whatever information processing these systems do — and if that matters morally, the vector framework gives us a more precise language for the discussion.

In clinical neuroscience, patients in altered states of consciousness — comatose patients, patients under anesthesia, patients in minimally conscious states — are currently assessed primarily through phi-based measurements. The vector framework suggests that some of these patients might have low depth of consciousness (low Depth in the topological sense) while occupying very different positions in (s, i, r) space. A patient with preserved recursion but disrupted integration might need different clinical management than a patient with the reverse profile. We offer this not as a clinical recommendation but as a hypothesis for future investigation.

7.3 The Independent Research Context

This work was conducted independently, without institutional affiliation and without external funding. We are aware that this is an unusual position from which to propose a revision of a dominant theory of consciousness.

We make no claim of priority over any specific result within the research programs of Tononi, Massimini, or others working on Integrated Information Theory. The question we are raising — whether phi is sufficient to characterize the form of consciousness, or only its level — is a question that can and should be addressed within those research programs, with resources and experimental access that we do not have.

What we offer is the formal framework, the mathematical grounding, the falsifiable prediction, and the preliminary literature review. The experimental verification requires resources we do not possess. We invite collaboration, criticism, and engagement from researchers who have those resources.

8. Conclusion

We began with the question of whether phi — the measure of integrated information — is sufficient to describe consciousness. Our answer is: phi describes how much consciousness a system has. It does not describe what form that consciousness takes.

The relational ontology presented in this paper proposes that the form of consciousness is described by a vector in a three-dimensional space of stability, integration, and recursion. This proposal is grounded in eight structural isomorphism tests across independent mathematical domains, formalized in Homotopy Type Theory, and used to generate a falsifiable prediction: two systems with comparable phi but different vectors should exhibit qualitatively different behavioral patterns.

A review of published behavioral literature confirms this prediction across six independent criteria, using the honeybee swarm and the cuttlefish as test systems. One technical gap remains: the measurement of phi for spatially distributed collective systems.

If the Vector Consciousness Prediction is confirmed experimentally, the consequence is not the replacement of Integrated Information Theory but its extension: phi tells you where a system is on the depth axis; the vector (s, i, r) tells you where it is in the full three-dimensional space. A complete theory of consciousness requires both.

The question of what consciousness is has been asked for as long as human beings have been conscious enough to ask it. We do not claim to have answered it. We claim to have made one aspect of it — the question of what forms consciousness takes across the diversity of life — more precise, more mathematical, and more testable than it was before.

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